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Pluvial Flooding:

A perspective prepared for the Flood Risk from Extreme Events (FREE) Steering Committee

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1. Introduction

Flooding may arise in several different ways: (i) through the inability of natural water courses to cope with excessive rainfall – fluvial flooding; (ii) through the inability of urban drainage systems (UDS) to cope with excessive rainfall – sewer surcharging; and (iii) direct runoff over land causing local flooding in areas not previously associated with natural or manmade water courses – pluvial flooding. Often these types of flooding occur together as a result of intense local rainfall for example the floods of June 2007 in Sheffield and Tewkesbury.

Following the floods in 2000 a new EA strategy has been developed 'Making space for water'. This strategy articulated the need for a risk-based approach, improvements in spatial planning and land use as well as the more traditional types of defence. There was a need to act upon:

- <u>Planning</u>: inappropriate flood plain development. The 1970-90s had seen a huge increase in flood plain development. However, the EA were now in a position to more strongly protest against such developments. There had been only 10 major developments in the last year which had gone ahead against EA advice.
- <u>Integrated urban drainage</u>: About 40% of flood damage was due to short duration rainfall (1-6 hours), and 80% of recent floods were due to surface water drainage Design criteria for urban drainage protection measures were based upon 1 in 10 year return period events; for river flooding 1 in 100 year events; and for coastal defences 1 in 200 year events.
- <u>Resilience and infrastructure</u>: Critical national assets were at risk from flooding. During the June floods the power supplies were disabled. In England and Wales there are 30 power stations, 187 fire station, 147 police stations, 407 A&E Clinics and Health Centres in moderate to severe flood risk zones. In addition, 2451 km of rail lines lie in flood zones, and thousands of electricity substations. The resultant Government Report (the Pitt Review) stressed the need for better analysis and forecasting of storms in and near urban areas.

In this paper we consider only pluvial flooding, although we recognise that, particularly in urban areas, the consequences of high intensity local rainfall may be wide ranging. Knowledge of the distribution of pluvial flooding has been limited until recently, although there has been considerable work on the occurrence of extreme rainfall which we outline first.

2. The frequency of occurrence of intense short-period rainfall

There has been considerable work to advance understanding of the frequency of occurrence of very intense rainfall for storm-water drainage design dating from the work of Bilham (1935) who published the empirical formula,

$$n = 1.25\ t\ (r+0.1)^{-3.55} \qquad (1)$$

where t = duration of rainfall in hours

n = number of occurrences in ten years
r = rainfall in inches

This formula was replaced for rainfall intensities greater than 1.25 inches per hour by Gumbel (1958) and Holland (1964) with

$$n = r \exp\,(1 - 0.8r/t)\,(r + 0.1)^{-3.55} \qquad (2)$$

This work was extended by Holland (1967) using data from the Cardington rainfall experiment leading to the design storm rainfall profile specified in the Road Research Laboratory Note 35. The methodologies currently used are articulated in the Flood Studies Report (FSR, 1975), the Flood Estimation Handbook (FEH,), and the soon to be published CEH Report for Defra and the EA. The Met Office Extreme Rainfall Alerts (ERAs) employ a single time-depth profile as given in Table 1.

Table 1: ERA thresholds

Duration (hours)	1	3	6
Rainfall depth (mm)	30	40	50

3. Forecasting pluvial flooding

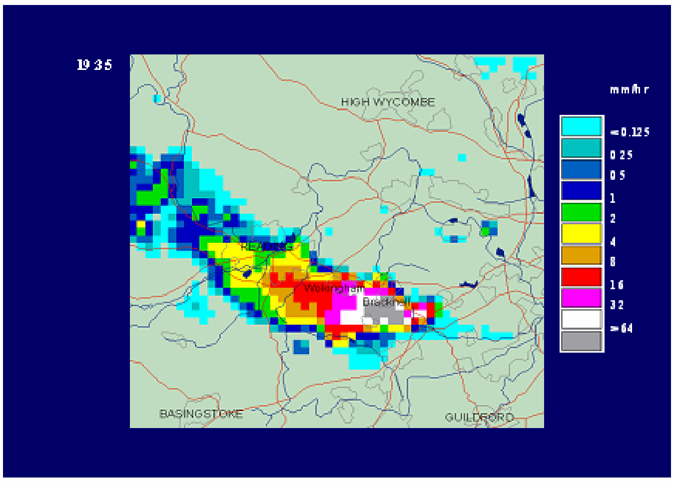
There are basically two components to pluvial flood forecasting namely the forecasting of intense local rainfall and forecasting where the water will collect on the surface. The second of these will depend upon whether the flow is on the surface, through pipes or in minor natural water courses. We discuss each of these separately.

3.1 Radar forecasting of intense local rainfall

The availability of digital weather radar from the 1970s onwards offered an opportunity to measure in real-time intense rainfall over wide areas from a single location with high spatial resolution. Although there were, and still are to some extent, many problems associated with radar measurements (see for example Collier, 1996), the potential of these data for forecasting in urban areas was recognised at an early stage (Austin and Austin, 1974,), and work continues to the present using high resolution ($1km^2$) radar data (see for example Adams, 2009). Figure 1 shows an example of intense rainfall from a thunderstorm.

Figure 1: Showing instantaneous rainfall rates(courtesy Me Office)

High resolution (1 km) radar imagery 7 May 2000



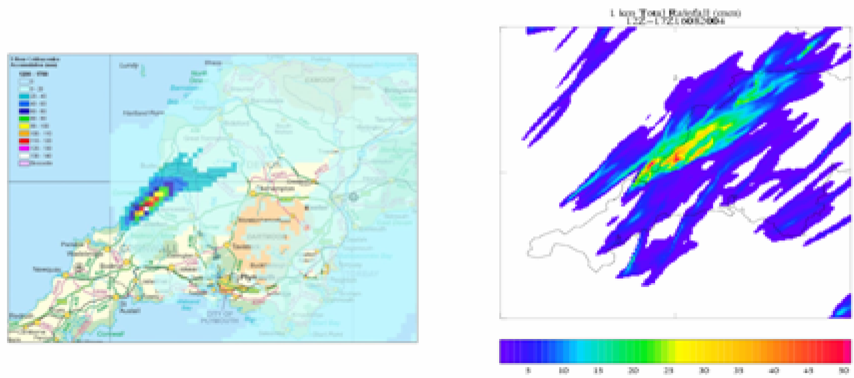
Over the last thirty years or so many of the problems with radar measurements have been overcome, or at least minimised. For example recent work on the Ottery St Mary hail storm has demonstrated a procedure for identifying hail (Hydro-Logic Report to the EA, 2009). The availability of dual polarisation techniques have enabled problems of attenuation to be removed enabling high resolution data to be acquired with practical size antennas. Techniques have now been developed to generate short-period probability flow forecasts based upon ensemble techniques using radar inputs to hydrological models (Collier, 2009; Germann et al, 2009).

3.2 High resolution Numerical Weather Prediction (NWP)models

Radar-based forecasts of intense rainfall for short (an hour or so) lead times are certainly very useful. However, for longer lead times NWP models offer the best prospect of useful forecasts. Increased computer power and improved physical process parameterisations with new methods of data assimilation have enabled intense rain producing convective systems to be resolved with resolutions of a few kilometres. Figure 2 illustrates the best achievable level of performance. The Met Office operational model will soon operate with a grid resolution of 1.5 km (see for example Golding et al, 2005), and make use of improved data assimilation methods including the assimilation of radar data. The Met Office also aim to implement an hourly rapid update cycle, and in the future intend to choose an appropriate methodology for data assimilation at the convective scale, which is already under test within FREE (Illingworth led project). Further work will also be put into the interpretation of the current deterministic outputs producing pseudo-ensembles to represent the positional uncertainties that are inevitable in such small scale events.

Figure 2

Illustrating Cobbacombe radar 5 hour total rainfall (mm) (left panel) and 1 km UM forecast rainfall (mm) for 12-17 UTC 16 August 2004 (from Golding et al, 2005)



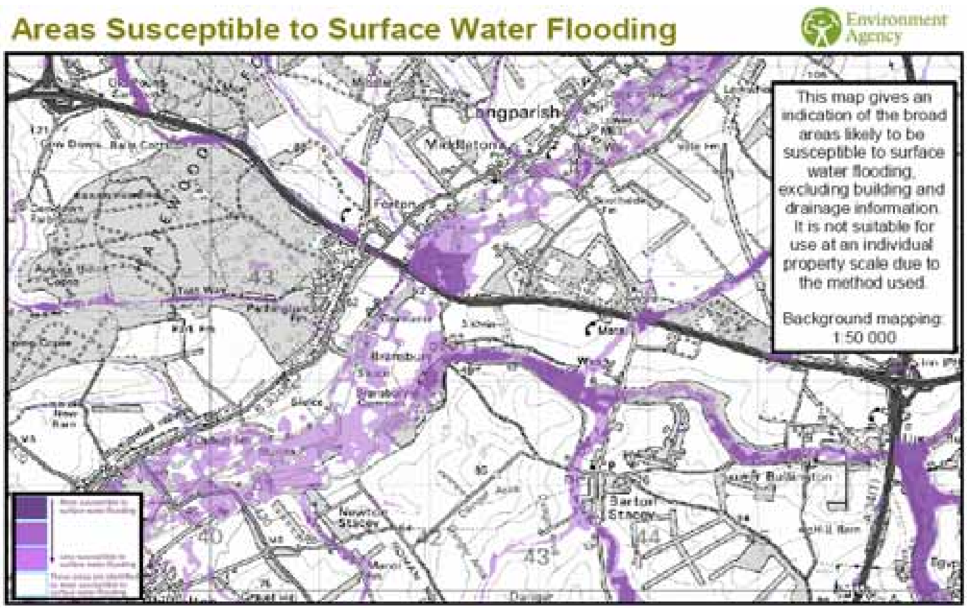
4. Forecasting where water collects

To forecast where intense rainfall will 'pond' on the surface away from natural water courses requires detailed knowledge of the ground surface and the urban morphology. The Environment Agency (EA) airborne laser data set provides such information from which the EA has produced a map of the envelope of surface water flooding, assuming no absorption by the sewerage and drainage systems. An example is shown in Figure 3 produced by a simple modelling technique. The method excludes buildings, and uses a single rainfall event of 6.5 hours duration and 0.5% probability (a 200 year return period rainfall event), routing water over a grid of 5 km x 5 km cells using Manning's equation.

This approach may be too limiting, and could lead to overstatement of the extent of flooding. The map is more likely to be accurate for steeper areas where inundation is influenced by topography rather than drainage and buildings. The map is likely to be less accurate over large, flat areas. There will be locations susceptible to surface water flooding outside of the 'less' susceptible areas of the map. The map is intended to help Local Resilience Forums and Regional Resilience teams plan their emergency response to surface water flooding. The data should only be used when supported with other information. It provides therefore only a general indication of areas which may be more likely to suffer from surface water flooding.

However, the Environment Agency is now working on fine tuning this type of map by using improved models and by looking at the most appropriate basis for planning. The flooding locations are being pre-computed for use with the real-time NWP rainfall forecasts. A surface water inundation / spreading / drainage model directly coupled to real-time rainfall (pseudo-ensemble) forecasts might provide a better approach than using the pre-calculated maps, although this remains to be investigated.

Figure 3: Showing a simple map overview of areas susceptible to surface water flooding, intended for emergency and broad scale land use planning only. The mapped data is split into three bands. These show areas graded between "less susceptible to surface water flooding" and "more susceptible to surface water flooding". The "more susceptible" band will generally be useful to help identify areas that are naturally most likely to flood first, or flood to the greatest depth. These areas are also more likely to flood during relatively frequent, less extreme events than areas falling into the other bands. (courtesy Environment Agency)



In urban areas the runoff comes mainly from impervious areas. However, the importance of the pervious areas and soil conditions have been recognised (DOE/NWC, 1983) for this 'runoff' and for the 'shallow sub-surface flow' it generates, for the pathways they offer for losses from the runoff, and for the effect of the flora they support under different climatic conditions. Responses in urban areas that, for example, increase green surface coverage (for example Gwilliam et al, 2006) or use more natural drainage systems such as 'Sustainable Drainage Systems' (SUDS) based on a range of infiltration and storage methods (see for example SEPA, 1999; Woods-Ballard et al, 2006) will require a better understanding of how these surfaces respond to direct rainfall and act as runoff pathways. Some guidance is already available for this from Balmforth et al (2006).

More recent work has implemented the concepts of (a) 'field capacity'; (b) 'rooting depth'; and (c) a linear Probability Distributed Model (PDM), with soil moisture capacity varying uniformly across the catchment from zero to a maximum. From this an expression can be derived linking the infiltration factor to the mean moisture content and mean moisture capacity. This has been successfully applied in the Revitalised Flood Hydrograph (ReFH) method (Kjeldsen et al, 2005) to update daily soil moisture estimates prior to a storm. However, during a storm event, drainage and evaporation are ignored and runoff is estimated by the linear PDM alone.

5. Opportunities for future work

Opportunities for work in FREE, or in subsequent projects, could include:

(a) Further investigation of the ERA thresholds, and how they might relate to Local Authority drainage standards. Also whether different intensity versus area relationships might be useful for EA regions.
(b) Further analysis of the results of the 2008 Met Office forecast trial.
(c) Further experimentation with the post-processing of the rainfall outputs to produce appropriate probability maps how often the thresholds are exceeded (building on Met Office existing work).
(d) Further work on refining the definition of the surface flood outline map.
(e) Coupling one or more surface water / drainage models to the Met Office real-time rainfall forecast suite to produce routine flood outlines followed by an evaluation of the results to analyse whether inter alia the rainfall accuracy is limiting the representation of the surface flow.
(f) Investigation of the generation of the uncertainties associated with modelling pluvial flooding including the use of various input data.

Acknowledgements

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